B_s^0 MIXING STUDIES AT THE TEVATRON

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Measurement of the B_s^0 oscillation frequency via B_s^0 mixing analysis provides a powerful constraint on CKM matrix elements. This note briefly reviews the motivation behind these analyses and describes the various steps that go into a mixing measurement. Recent results on B_s^0 mixing obtained by the CDF and DØ collaborations using the data samples collected at Tevtron Collider in the period 2002 - 2005 are presented.

1 Introduction

Mixing is the process whereby some neutral mesons change from their particle to their anti-particle state, and vice versa. This kind of oscillation of flavor eigenstates into one another was first observed in the K^0 meson system. It has since then been seen for B mesons, first in an admixture of B_d^0 and B_s^0 by UA1[1] and then in B_d^0 mesons by ARGUS [2]. The combinations of these results already indicated that the frequency of B_s^0 mixing oscillations was higher than the frequency of B_d^0 oscillation. The frequency of the oscillation is proportional to the small difference in mass between the two eigenstates, Δm, and for the $B_d^0 - \bar{B}_d^0$ system can be translated into a measurement of the CKM element $|V_{td}|$. Δm_d has been precisely measured (the world average is $\Delta m_d = 0.502 \pm 0.007$ ps^{-1}) [3] but large theoretical uncertainties dominate the extraction of $|V_{td}|$ from Δm_d. This problem can be reduced if the B_s^0 mass difference, Δm_s, is also measured. $|V_{td}|$ can then be extracted with better precision from the ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m(B_s^0)}{m(B_d^0)} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 \tag{1}$$

where ξ is estimated from Lattice QCD calculations to be $1.15 \pm 0.05^{+0.12}_{-0.00}$ [3]. The above has motivated many experiments to search for B_s^0 oscillations though a statistically significant signal hasn't been observed before this work, a lower limit of $\Delta m_s > 16.1$ ps^{-1} at 95% C.L.[3] has been

set. Since this current limit indicates that the B_s^0 oscillations are at least 30 times faster than the B_d^0 oscillations, a B_s^0 mixing measurement is experimentally very challenging. If the Standard Model is correct, then Δm_s is expected from global fits to the unitarity triangle to be in the range $(16.2 - 24.5)$ ps^{-1} at the one standard deviation confidence level [4].
In the B_s^0-$\bar{B}_s^0$ system there are two mass eigenstates, the heavier (lighter) one having mass M_H (M_L) and decay width Γ_H (Γ_L). Denoting $\Delta m_s = M_H - M_L$ and $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, the time dependent probability that a B_s^0 oscillates into a $\bar{B}_s^0$ (or vice versa) is given by $P^{\rm osc} = \Gamma e^{-\Gamma t}(1 - \cos\Delta m_s t)/2$ while the probability that the B_s^0 does not oscillate is given by $P^{\rm nos} = \Gamma e^{-\Gamma t}(1 + \cos\Delta m_s t)/2$, assuming that $\Delta\Gamma_s$ is small and neglecting CP violation.

2 Tevatron Detectors

2.1 CDF detector

The CDF detector is described in detail elsewhere [5]. The components most relevant to this analysis are briefly described here. The tracking system is in a 1.4 T axial magnetic field and consists of a silicon microstrip detector surrounded by an open-cell wire drift chamber (COT). The muon detectors used for this analysis are the central muon drift chambers (CMU), covering the pseudorapidity range $|\eta| < 0.6$, and the extension muon drift chambers (CMX), covering $0.6 < |\eta| < 1.0$, where $\eta = -\ln[(\tan(\theta/2)]$ and θ is the polar angle.

2.2 DØ detector

The DØ detector is described in detail elsewhere [6]. The central tracking and muon systems are the components most important to this analysis. The central tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing for pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively. An outer muon system, at $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids [7].

3 Analysis Technique

The analysis starts with the reconstruction of the final state of the B_s^0 meson. At CDF, the B_s^0 mesons reconstructed in semileptonic as well as in hadronic decays of B_s^0. DØ uses only the semileptonic decays of the B_s^0 meson for the final state reconstruction. CDF has about 18,200 $B_s^0 \to D_s^-(\to \phi\pi)\mu^+ X$ in 765 pb^{-1} of data. It also has about 2300 B_s^0 signal candidates in Hadronic channels. DØ analyzes 1 fb^{-1} of data and reconstruct $26,710 \pm 560$ events in the decay $B_s^0 \to D_s^-(\to \phi\pi)\mu^+ X$.

In order to know the initial flavor of the B_s^0 mesons, an Initial State Flavor tagging technique is used. The second B meson (or baryon) in the event was used to tag the initial flavor of the reconstructed B^0 meson. The tagging technique utilized information from identified leptons (muons and electrons) and reconstructed secondary vertices. For reconstructed $B_s^0 \to D_s^- \mu^+ X$ decays both leptons having the same sign would indicate that one B hadron had oscillated while opposite signs would indicate that neither (or both) had oscillated. The performance of the flavor tagging is characterized by the efficiency, $\epsilon = N_{\rm tag}/N_{\rm tot}$, where $N_{\rm tag}$ is the number of tagged B_s^0 mesons, and $N_{\rm tot}$ is the total number; the tag purity η_s, defined as $\eta_s = N_{\rm cor}/N_{\rm tag}$, where $N_{\rm cor}$ is the number of B_s^0 mesons with correct flavor identification; and dilution, related to purity as $\mathcal{D} = 2\eta_s - 1$. The tagging can be performed on the opposite side as well as on the same side of the reconstructed B_s^0 meson. Three main tagging algorithms were used in the present analysis viz. Soft Lepton Tagging (where lepton could be a muon or

an electron), Jet Charge Tagging and Same Side Tagging (only at CDF). The performance of the CDF's combined Opposite Side Tagging (OST) is, $\epsilon D^2 = (1.55 \pm 0.020 \pm 0.014)\%$. The Same Side Tagging (SST) Performance is, $\epsilon D^2 = (4.0 + 0.9 - 1.2)\%$. The DØ combined OST Performance is, $\epsilon D^2 = (2.48 \pm 0.21 + 0.08 - 0.06)\%$. The taggers were tuned by measuring the B_d^0 mixing oscillations and DØ finds $\Delta m_d = 0.506 \pm 0.020 \pm 0.014$ ps^{-1} in good agreement with the world average of $\Delta m_d = 0.502 \pm 0.007$ ps^{-1} [3]. After applying the tagging to the DØ data, 5601 ± 102 tagged events were found.

Once the tagging is performed, the proper decay time of candidates is needed. The proper decay length of each B_s^0 mesons is found as $ct_{B_s^0} = (\vec{L}_T \cdot M_{B_s^0}/(p_T^{B_s^0})$, where $\vec{L}_T$ is the vector in the transverse plane from the primary to the B_s^0 decay vertex, and $M_{B_s^0} = 5.3696$ GeV [3]. However, in the case of semileptonic B_s^0 decay, the undetected neutrino does not allow a precise determination of the meson's momentum and Lorentz boost. To take into account the effects of neutrinos and other lost or non-reconstructed particles, a K factor was estimated from Monte Carlo (MC) simulation by finding the distribution of $K = p_T(\mu D_s)/p_T(B)$ for a given decay channel. The proper decay length of each B_s^0 meson is then $ct_{B_s^0} = l_M \cdot K$, where $l_M = (\vec{L}_T \cdot \vec{p}_T^{\mu D_s^-})/(p_T^{\mu D_s^-})^2 \cdot M_{B_s^0}$ is the measured visible proper decay length (VPDL). The VPDL uncertainty was determined by the vertex fitting procedure and track parameter uncertainties. To account for possible mismodeling of detector uncertainties, resolution scale factors were introduced as determined by examining the pull distribution of the the vertex positions of a sample of $J/\psi \to \mu\mu$ decays.

4 Results and Conclusions

Using the Amplitude Fit Method [8] and 365 pb $^{-1}$ of data, CDF puts a limit on B_s^0 oscillations frequency of 8.6 ps^{-1} and sensitivity of 13.0 ps^{-1} at 95% C.L. DØ using the similar method finds

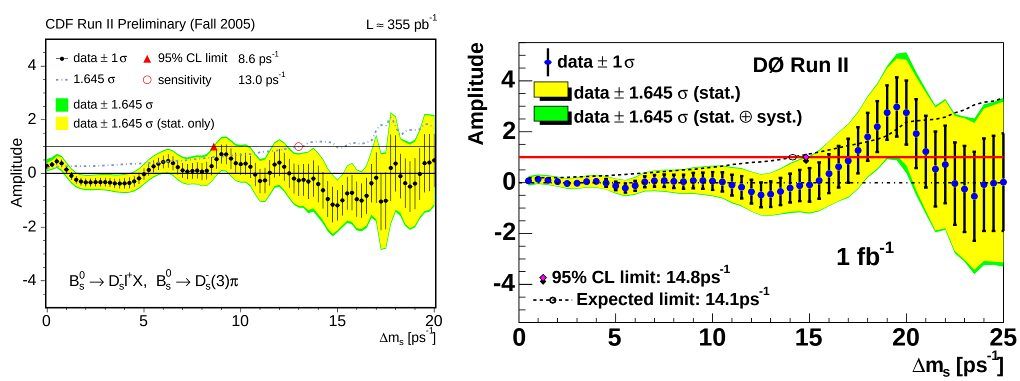

Figure 1: Amplitude fit Scan for CDF (left) and DØ (right) data.

a limit of 14.8 ps^{-1} and sensitivity of 14.1 ps^{-1} at 95% C.L. DØ also performed a likelihood scan as a function of Δm_s. Figure 2 shows the value of $-\Delta \log \mathcal{L}$ as a function of Δm_s, indicating a favored value of 19 ps^{-1}, while variation of $\log \mathcal{L}$ from the minimum indicates an oscillation frequency of $17.0 < \Delta m_s < 21.0$ ps^{-1} at the 90% C.L. The uncertainties are approximately Gaussian inside this interval. The parametrized MC test shows that for a true value of $\Delta m_s =$ 19 ps^{-1}, the probability was 15% for measuring a value in the range $17.0 < \Delta m_s < 21.0$ ps^{-1} with a -$\Delta \log \mathcal{L}$ lower by at least 1.9 than the corresponding value at $\Delta m_s = 25 ps^{-1}$. [9]

To test the statistical significance of the observed minimum, an ensemble test using the data sample was performed by randomizing the flavor tag and retaining all other information for the candidate, effectively simulating a B_s^0 oscillation with an infinite frequency. The ensemble test results shows that the probability to observe a minimum in the range $16.0 < \Delta m_s < 22.0$ ps^{-1}

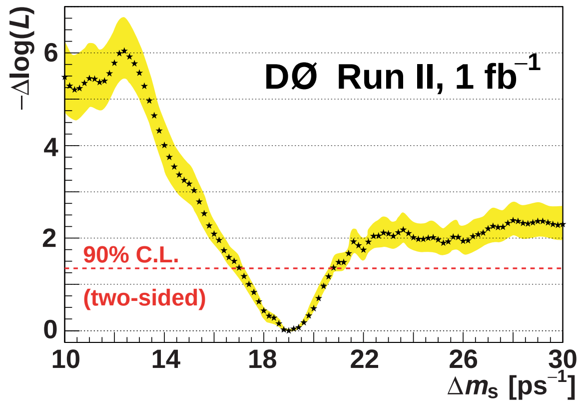

Figure 2: Likelihood Scan plot for DØ data. Yellow band shows the effect of systematics.

with a decrease in $-\log\mathcal{L}$ with respect to the corresponding value at $\Delta m_s = 25$ ps^{-1} of more than 1.7, corresponding to our observation including systematic uncertainties, was found to be $(5.0 \pm 0.3)\%$. This range of Δm_s was chosen to encompass the world average lower limit and the edge of our sensitive region.

5 outlook

Further improvements are planned for future which includes improvements both in detector and analysis technique. After this conference, CDF updated their B_s^0 mixing analysis and the latest CDF results can be found here [10].

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